

# Dark Energy in The Universe Finally a 2<sup>nd</sup> Opinion!

“CHANDRA CLUSTER COSMOLOGY PROJECT III:  
COSMOLOGICAL PARAMETER CONSTRAINTS”  
Vikhlinin et al. 2008 (arXiv:0812.2720v1)

*Michael Way*  
*NASA/GISS, NASA/Ames, QC/CUNY*

# Dark Energy in the news!?

[http://www.nytimes.com/2008/12/17/science/space/  
17darkside.html](http://www.nytimes.com/2008/12/17/science/space/17darkside.html)

”Measuring the Mysterious ‘Dark’ Force”

By Dennis Overbye (December 16, 2008)

*[http://www.nytimes.com/2008/12/17/science/space/  
17dark.html](http://www.nytimes.com/2008/12/17/science/space/17dark.html)*

*“Dark Energy Stunts Galaxies’ Growth”*

*The Economist: “A Shot in the Dark” (Dec 20, 2008)*

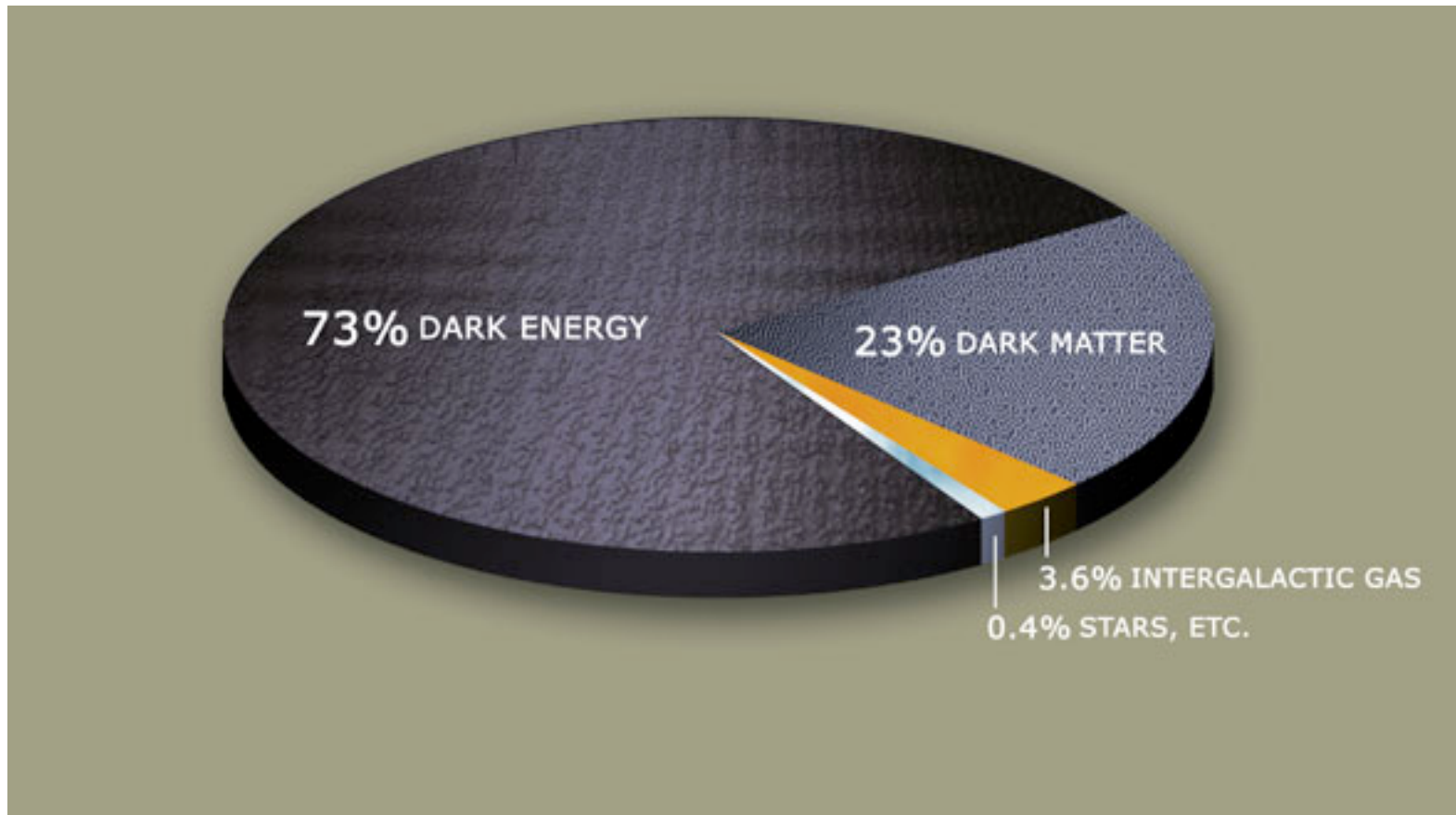
*[http://www.economist.com/science/displaystory.cfm?  
story\\_id=12811351](http://www.economist.com/science/displaystory.cfm?story_id=12811351)*

# What's on the menu today?

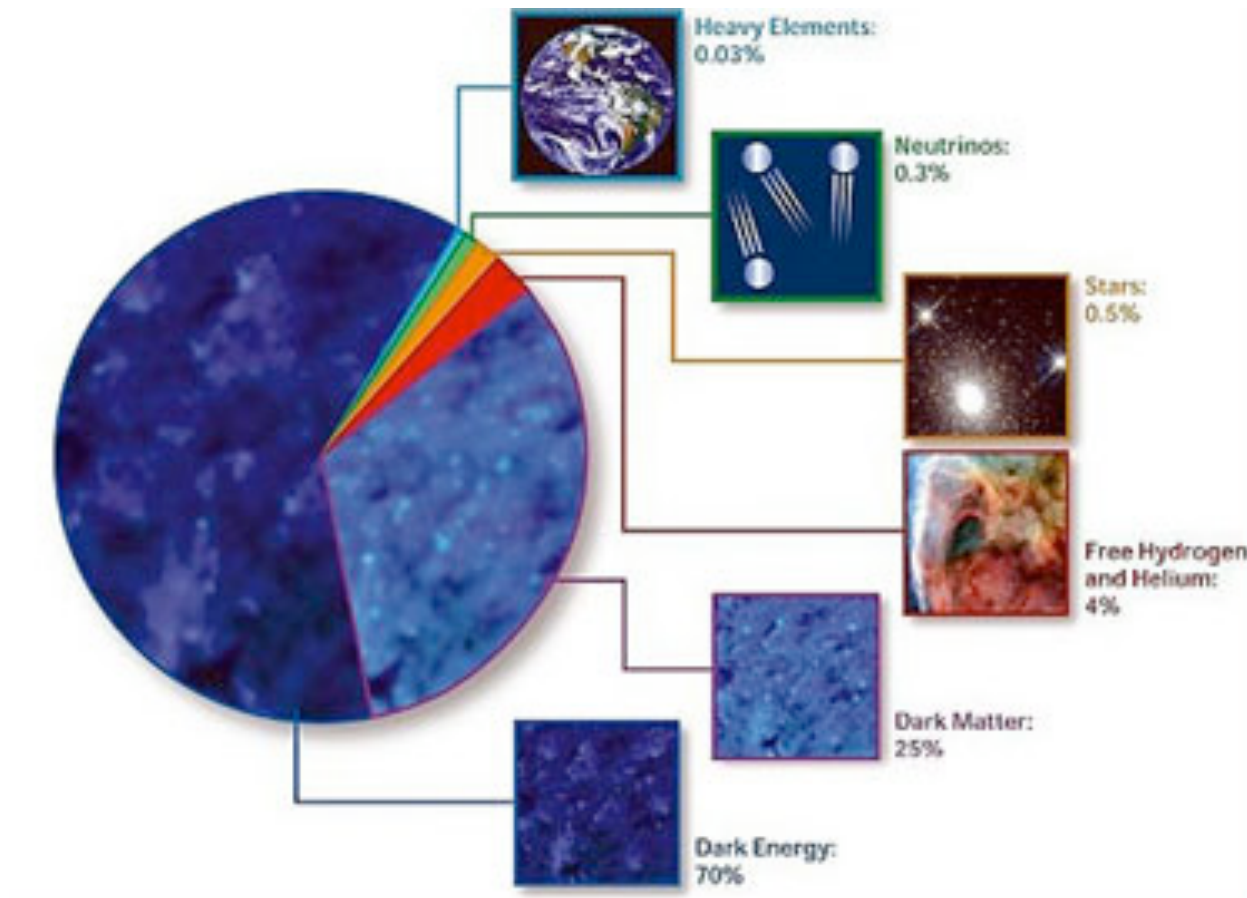
- 1.) What is our universe made of? What is its density?
- 2.) What are the different kinds of universes possible?
- 3.) What is Dark Matter – what is the evidence today?
- 4.) What is Dark Energy – what was the evidence?
- 5.) What is Dark Energy – what is the new evidence?
- 6.) What should you take away from today's talk?

What is The Universe made of?  
Not the same stuff as us, that's for sure:

$$\Omega = \Omega_{Matter} + \Omega_{\Lambda} = 0.27 + 0.73 = 1$$



# What is The Universe made of?



# What is this $\Omega=1$ parameter?

The Theory of Inflation requires us to have a flat universe with  $\Omega=1$

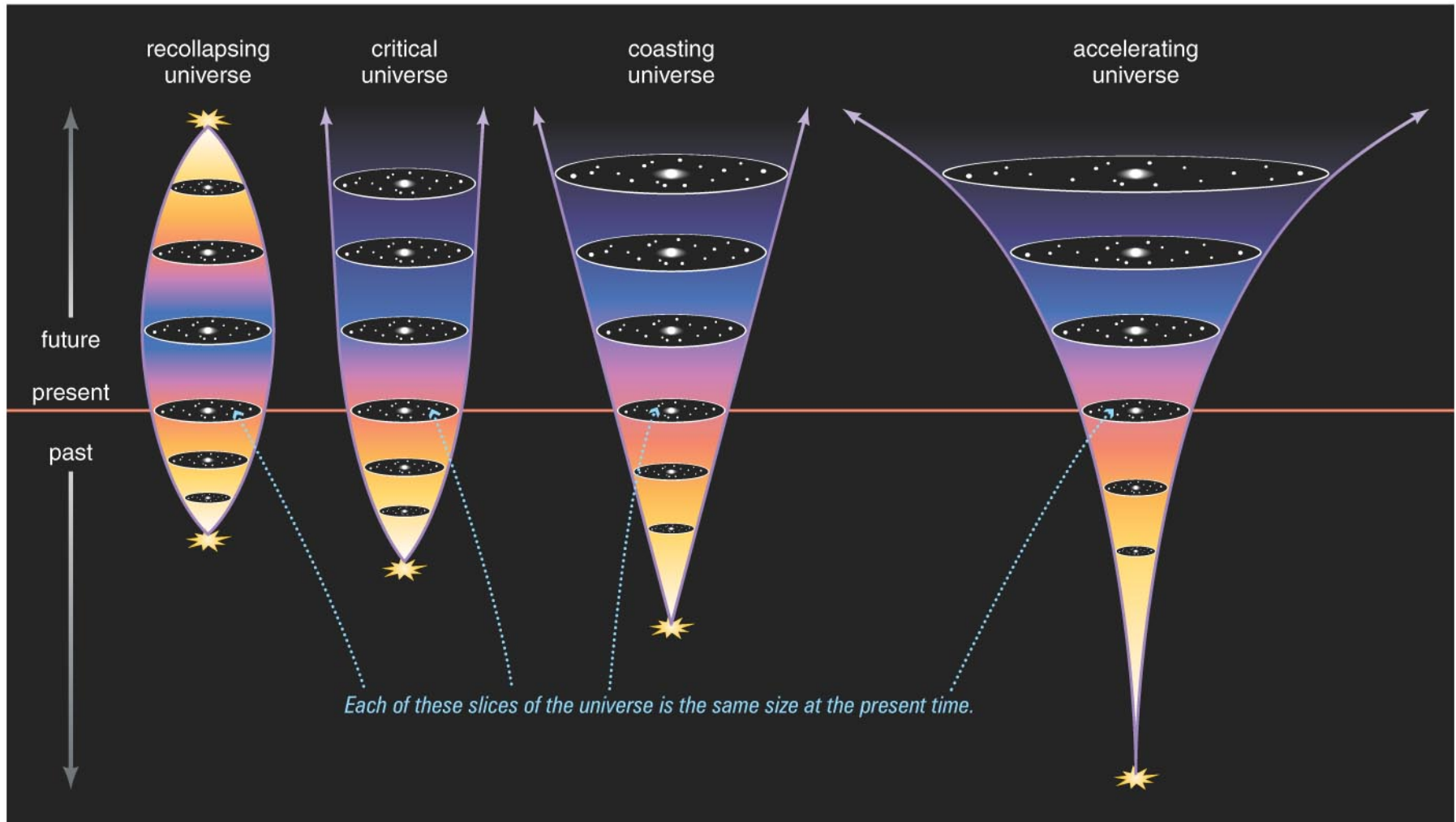
WMAP gives very good constraints on  $\Omega=1$

$\Omega$  = average matter density/critical density

[Regardless of the **type** of universe we live in]

- Inflation helps theorists to explain how the large scale structures we see in the universe today evolved from the primeval universe.
- Also explains how the universe is flat (Euclidean), homogeneous and isotropic (on large scales)
- A recent review of inflation can be found here:  
<http://arxiv.org/abs/0901.0549>

# What types of Universe are there?

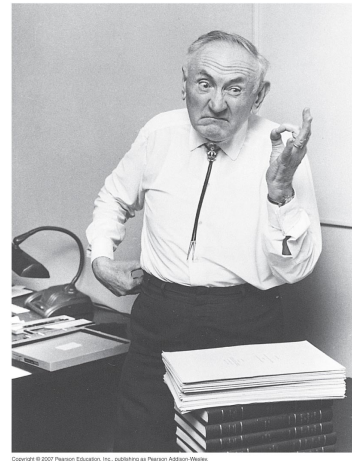


# What is Dark Matter?

A form of matter that only interacts with other matter via the gravitational force

Evidence:

- Galaxy Rotation Curves  
(Vera Rubin 1975)
  - They do not fall as a function of radius
- Clusters of Galaxies  
(Fritz Zwicky 1933)
  - High Mass to light ratio

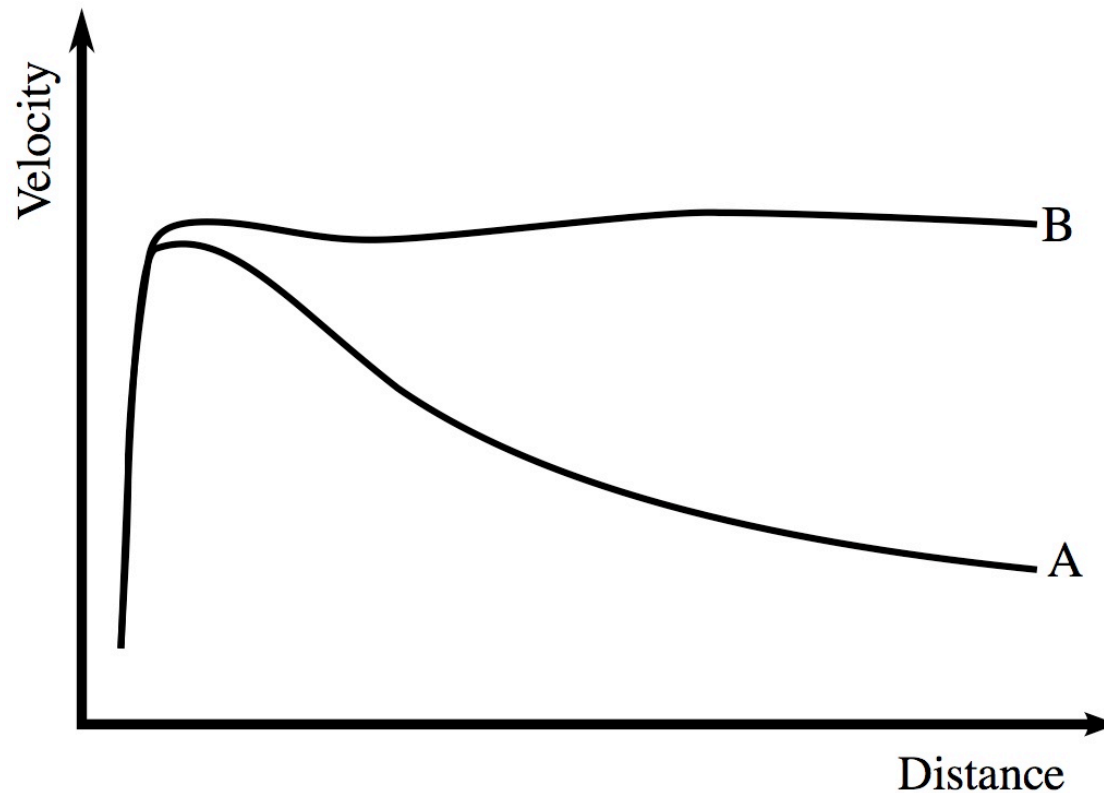




# Galaxy Rotation Curves

A: Predicted based on luminous matter

B: Observed from stellar orbits



# Clusters of Galaxies

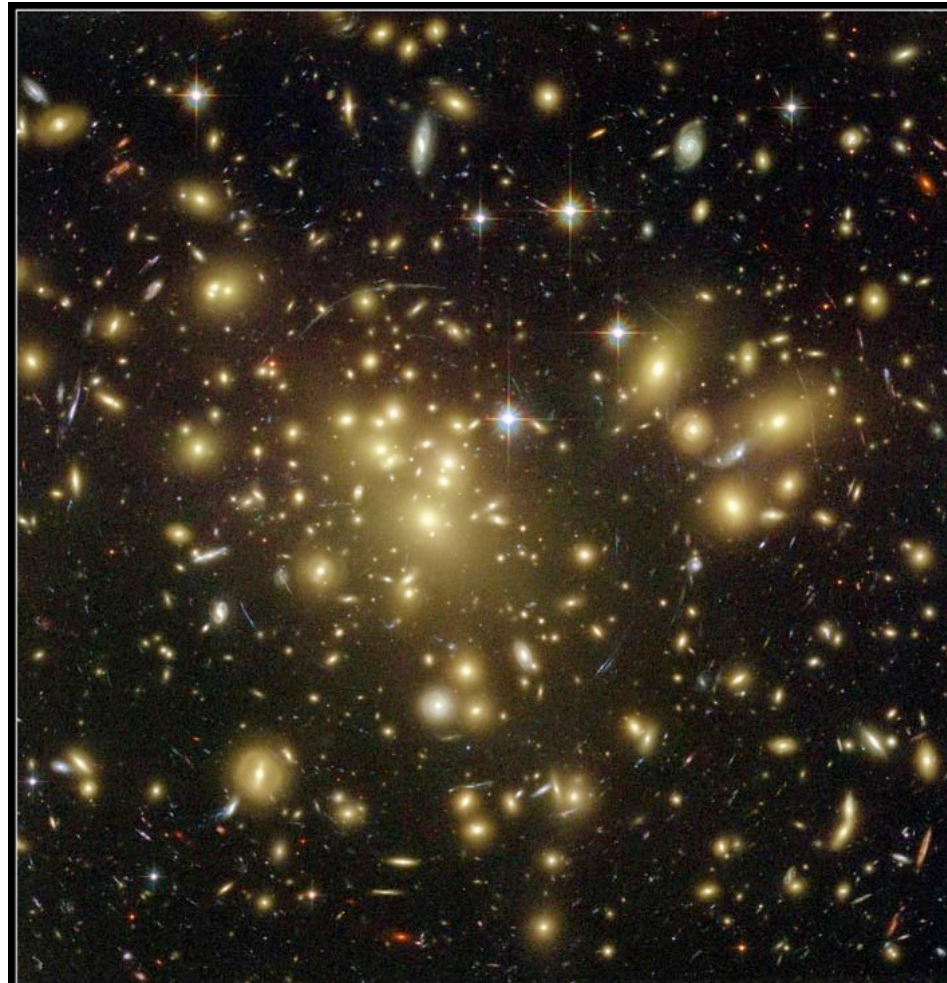
Virial Theorem: Relates the total KE (over time) of a stable system to the total PE:

$$2\langle T \rangle = - \sum_{k=1}^N \langle F_k \cdot r_k \rangle$$

Zwicky (1933)

- Estimate 1: total mass of Coma cluster based on motions of galaxies
- Estimate 2: total mass based on number of galaxies and their brightness
- They differed by a factor of about 400
- Later confirmed by X-ray and Gravitational Lensing

# Clusters of Galaxies/Grav Lensing



**Galaxy Cluster Abell 1689**  
Hubble Space Telescope • Advanced Camera for Surveys

# What is Dark Energy?

A positive cosmological constant which manifests itself as a negative pressure in Einstein's Field Equations,  $\Lambda=0.73$

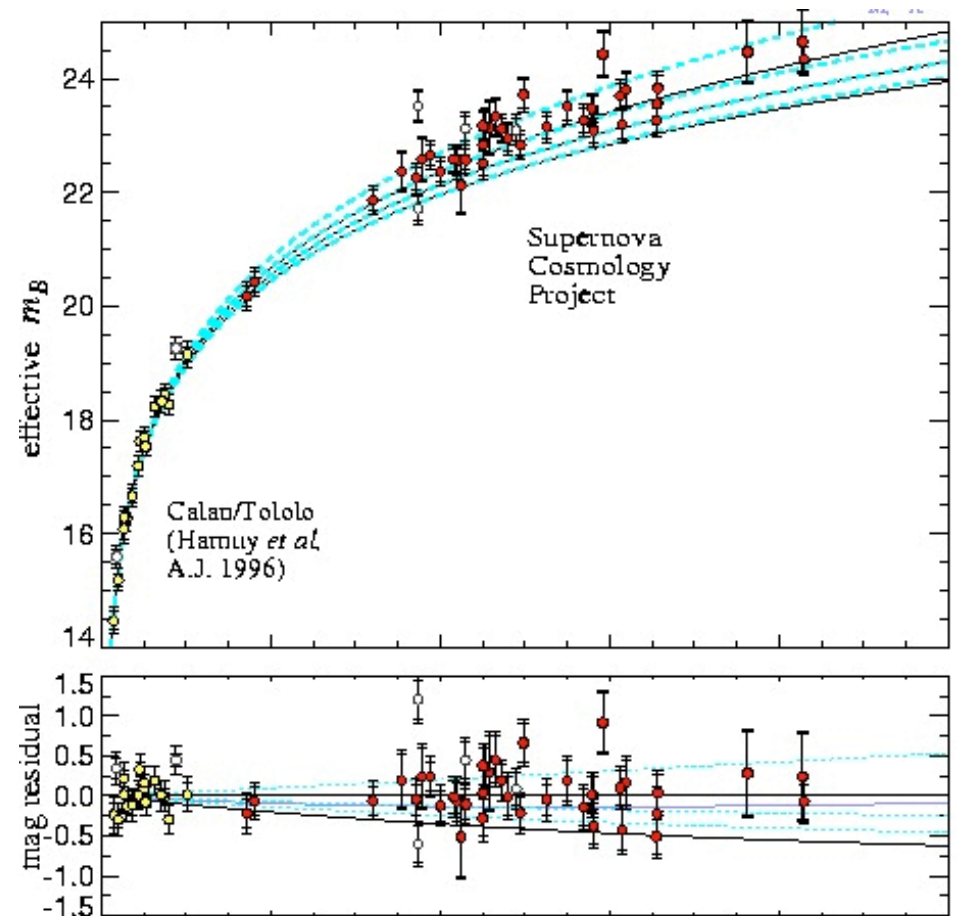
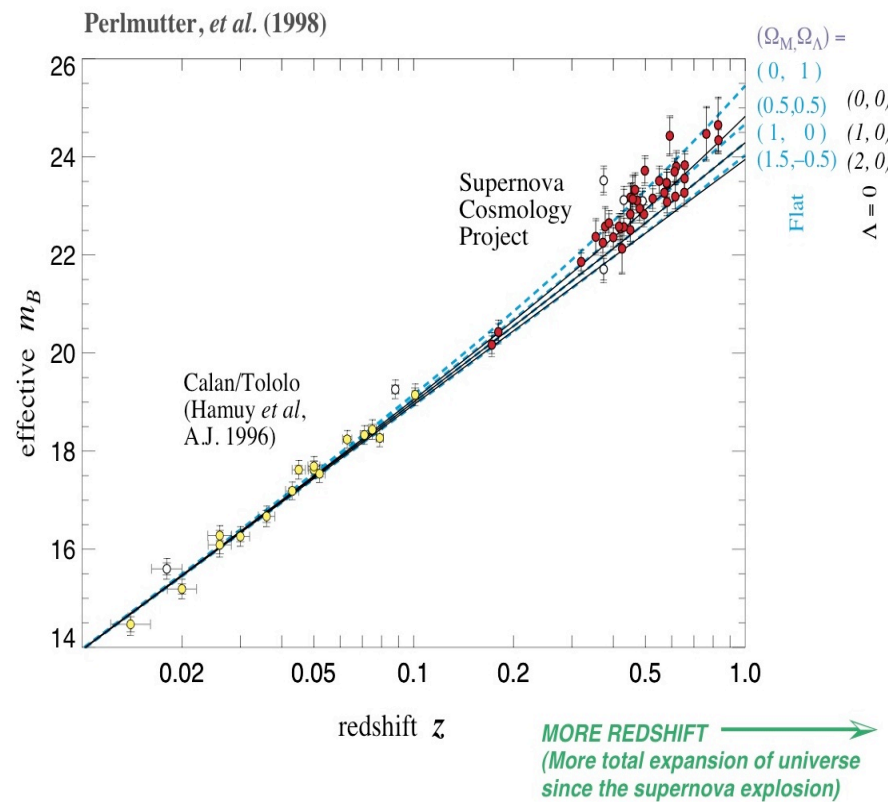
$$G_{ab} + \Lambda g_{ab} = kT_{ab}$$

Evidence:

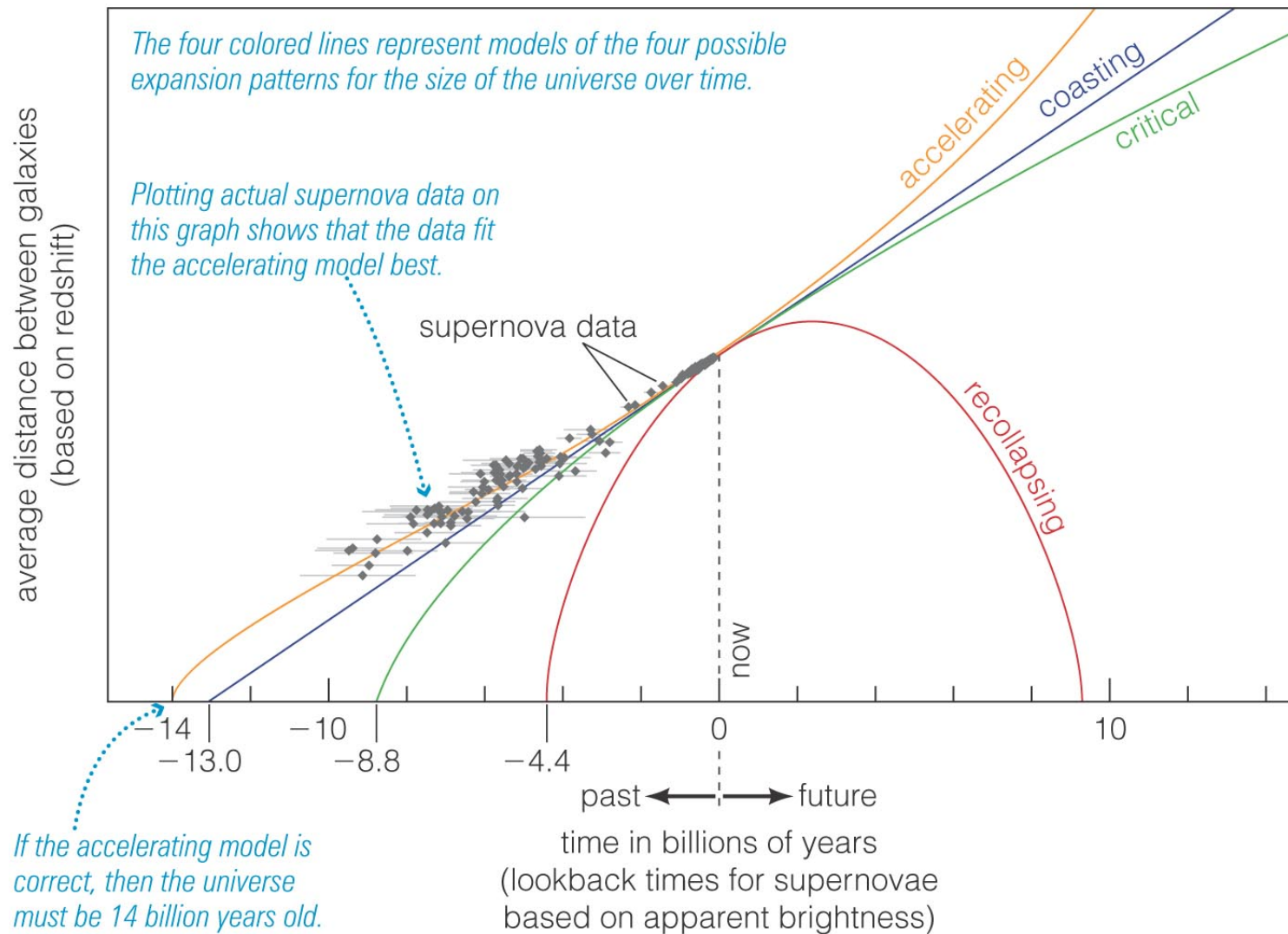
- High Redshift Supernovae
  - Farther away than they should be otherwise
- X-ray Clusters of Galaxies (Vikhlinin 2008)
  - They are evolving too slowly
  - <http://arxiv.org/abs/0812.2720>

# High-z Supernovae Evidence

↑  
FAINTER  
(Farther)  
(Further back in time)



# High-z Supernovae Evidence





# X-ray Cluster Evidence (2008/12)

- **We Know:** Growth of structure & distance-redshift relation sensitive to DE properties
- **Evidence Based on:** Evolution in number density of massive clusters of galaxies
- **Actually use:** Evolution over time of cluster mass function to trace growth of density perturbation from the early universe
  - Mapping btwn linear power spectrum & cluster mass fcn relies on model for non-linear gravitational collapse (via n-body simulations)
  - Mass density recently dominated by CDM and Gaussian fluctuations
  - Must use  $H_0$  from Hubble Project

# X-ray Cluster Evidence (2008/12)

- Two samples used (Universe today  $\sim 13.6$  Gy)
  - 43  $\langle z_L \rangle \sim 0.05$  ( $\sim 0.6$  Gyr ago, Universe  $\sim 13.001$ )
  - 37  $\langle z_H \rangle \sim 0.5$  ( $\sim 5$  Gyr ago, Universe  $\sim 8.6$  Gy)
- Targets/Samples
  - ROSAT PSPC 400d sample for high- $z$
  - Chandra deep imaging to get mass
- Mass proxies (checked via simulations)
  - Average X-ray temp ( $T_x$ ) in annulus  $(0.15-1)r_{500\text{kpc}}$ 
    - Avoids radiative cooling effects in central regions
  - Intracluster gas mass ( $M_{\text{gas}}$ ) integrated within  $r_{500}$
  - Combination of the two estimates  $Y_x = T_x \times M_{\text{gas}}$



# Vikhlinin et al. 2008 evidence

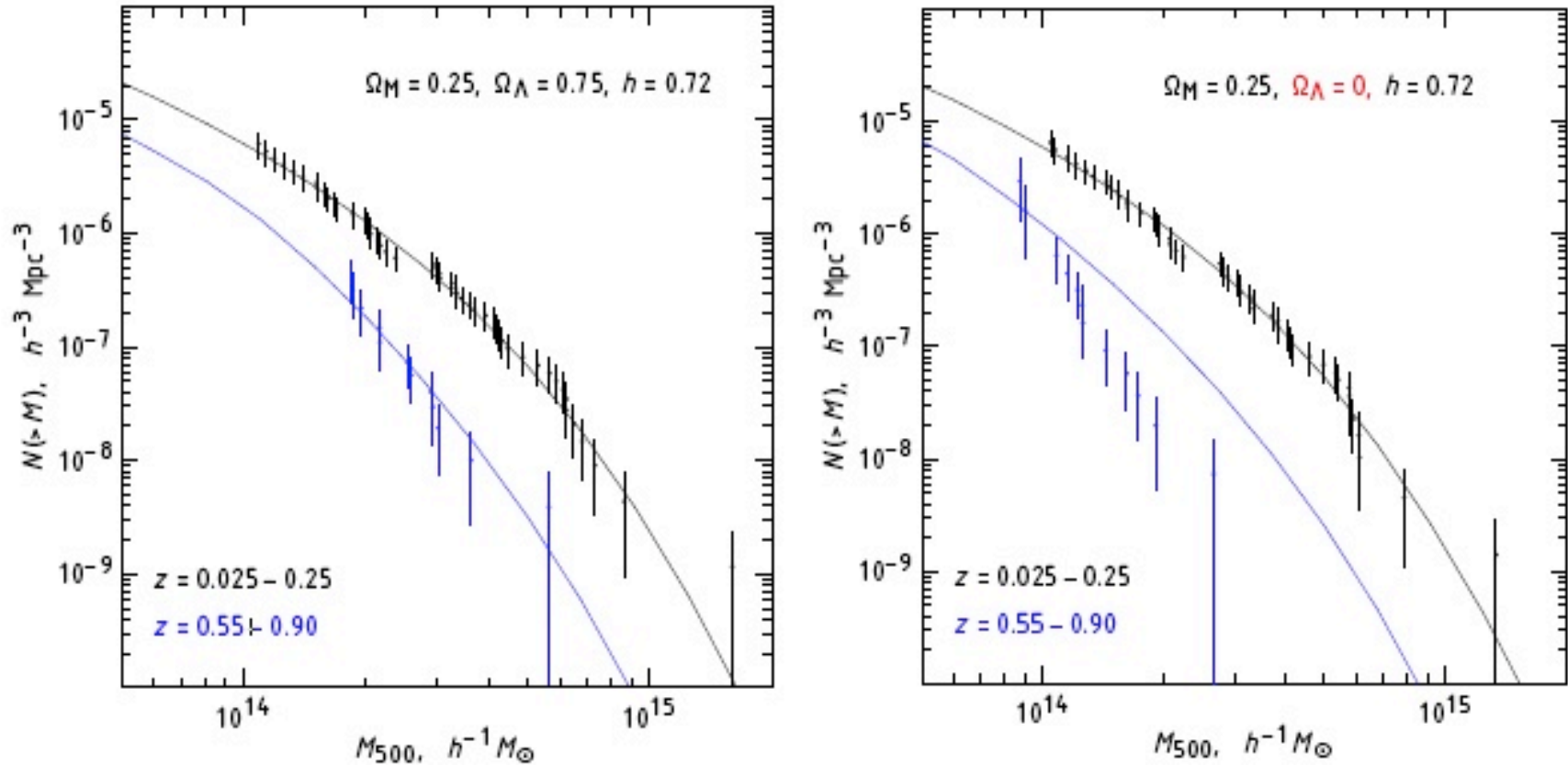
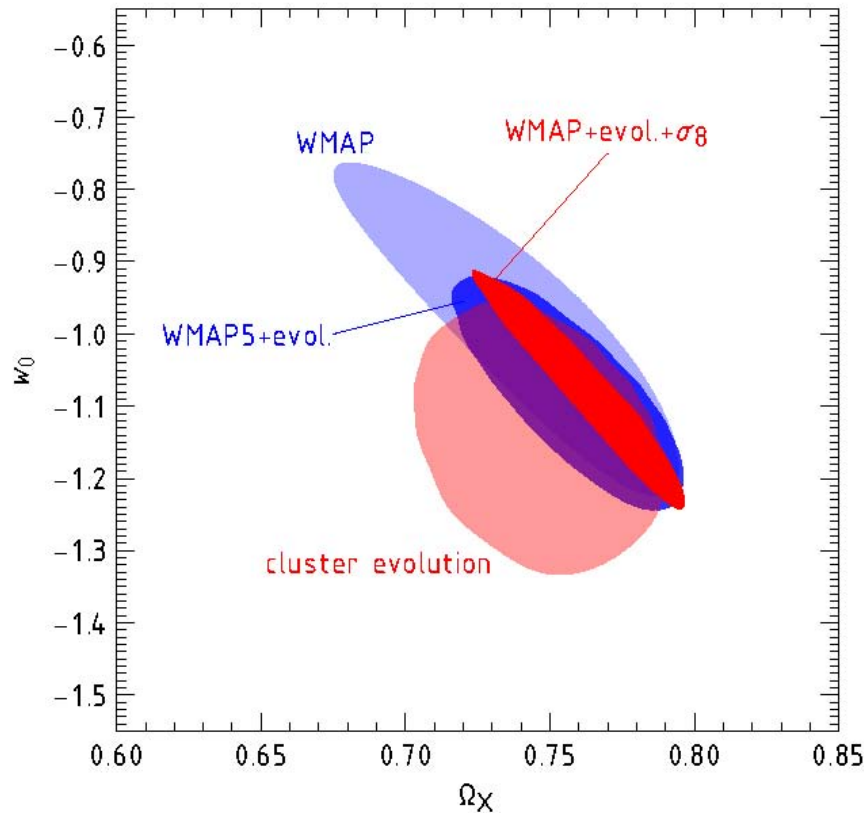
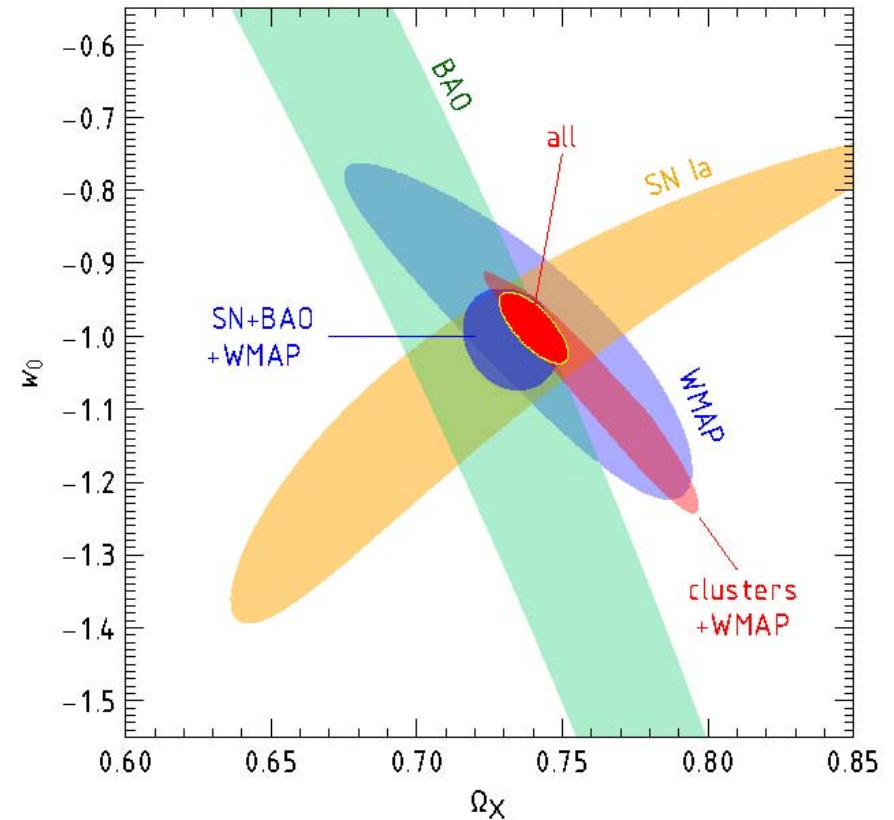


FIG. 2.— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at  $z = 0$  adjusted) computed for a cosmology which is close to our best-fit model. The low- $z$  mass function is reproduced from Fig. 1 which for the high- $z$  cluster we show only the most distant subsample ( $z > 0.55$ ) to better illustrate the effects. In the right panel, both the data and the models are computed for a cosmology with  $\Omega_{\Lambda} = 0$ . Both the model and the data at high redshifts are changed relative to the  $\Omega_{\Lambda} = 0.75$  case. The measured mass function is changed because it is derived for a different distance-redshift relation. The model is changed because the predicted growth of structure and overdensity thresholds corresponding to  $\Delta_{\text{crit}} = 500$  are different. When the overall model normalization is adjusted to the low- $z$  mass function, the predicted number density of  $z > 0.55$  clusters is in strong disagreement with the data, and therefore this combination of  $\Omega_M$  and  $\Omega_{\Lambda}$  can be rejected.

# Vikhlinin et al. 2008 evidence



Dark Energy constraints in a flat universe from combination of the CMB and cluster data. Adding  $\sigma_8$  vs CMB normalization significantly improves things



Dark Energy constraints in a flat universe from combination of all cosmological data sets.  $w_0$ =equation of state  
 $w_0$ =dark energy pressure/density

# What to take away?

We now have two independent lines of evidence for Dark Energy (or a negative pressure pervading The Universe)

- 1.) High- $z$  Supernovae data are fainter than they would be w/o Dark Energy
- 2.) The predicted number density of  $z > 0.55$  massive X-ray clusters of galaxies is in strong disagreement with a model Universe w/o Dark Energy